# A Model Qubit Using Optics and Microwaves with the NV-Center in Diamond

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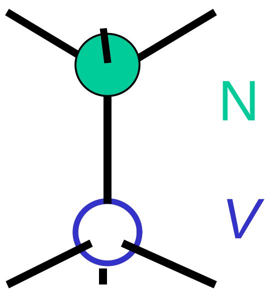
# Outline




- Background
- The Qubit (NV Center)
- Gate Operations and Lifetimes
- Next Step: CNOT gate
- Summary

# Background

- Previous work on NV
  - Optical and EPR (Davies and Hamer, Loubser and van Wyk)
  - Zero-field ODMR (van Oort and Glasbeek)
  - Level-crossing spectroscopy (Manson et al.)
  - Single-defect spectroscopy (Wrachtrup et al.)
- Other QI applications using NV
  - $^{13}C$ nuclear spins as qubits/rf pulse gates

    J. Wrachtrup et al., Optics and Spectroscopy **91**, 429 (2001)
  - Cavity dark states

    M.S. Shahriar et al., Opt. Commun. **195**, 411 (2001)
  - NV as a single-photon source

    C. Kurtsiefer et al., Phys. Rev. Lett. **85**, 290 (2000)

    A. Beveratos et al., Phys. Rev. A **64**, 061802 (2001)

## Criteria

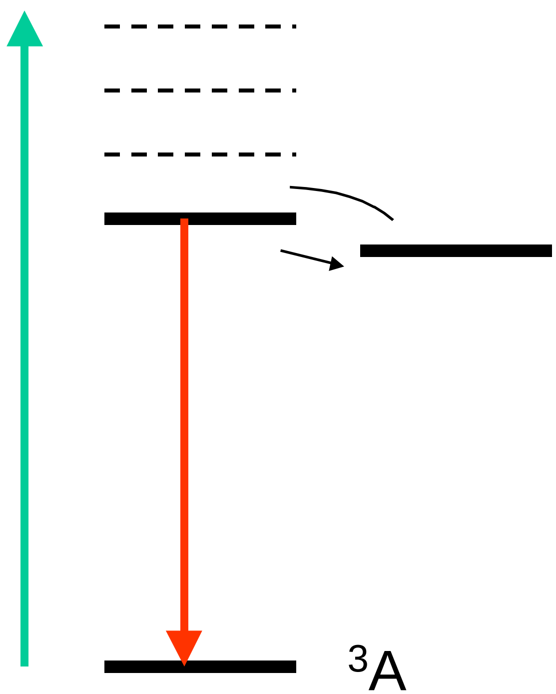
- Well-Defined Hilbert Space
- Prepare in Ground State
- Low Decoherence Rate
- Available Gate Operations
- Single-Quantum Measurements

## Physical Implementation

- Electron spin states
- Polarize optically
- Operate with microwave pulses
- Detect the result optically

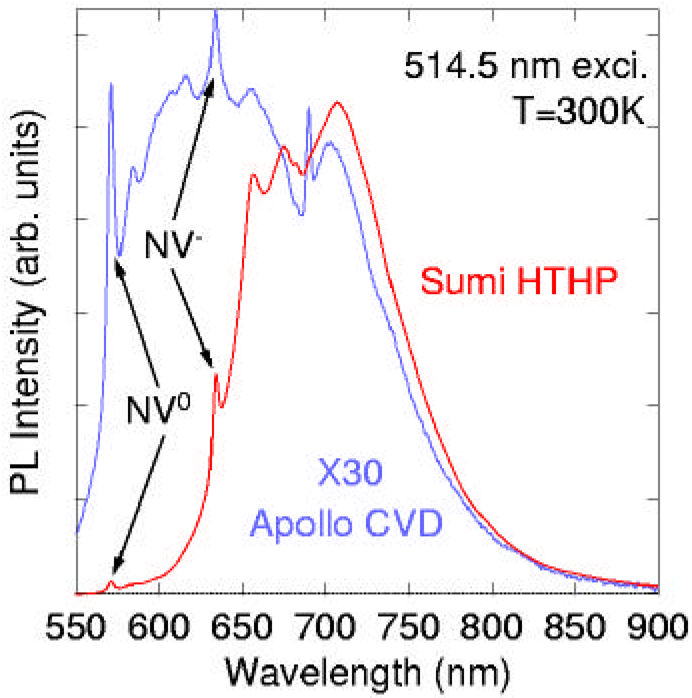
DiVincenzo and Loss, Superlattices and Microstructures **23**, 419 (1998)

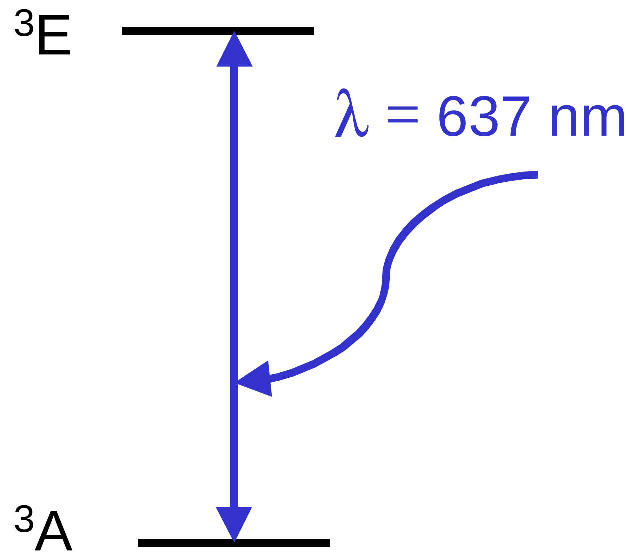
# The Optical Cycle Produces Spin polarization



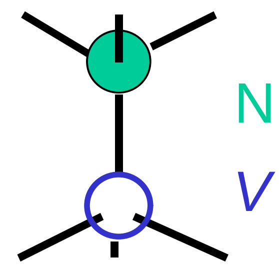

- 532 nm cw excitation
- Cycle
  - Excitation
  - Radiationless decay
  - Radiative decay to ground state--100MHz
  - *Intersystem Crossing--not spin conserving*
    - *2 MHz out*
    - *Thermally activated back*
- ~1 kHz rate

# The NV Center Qubit--Optical Detection

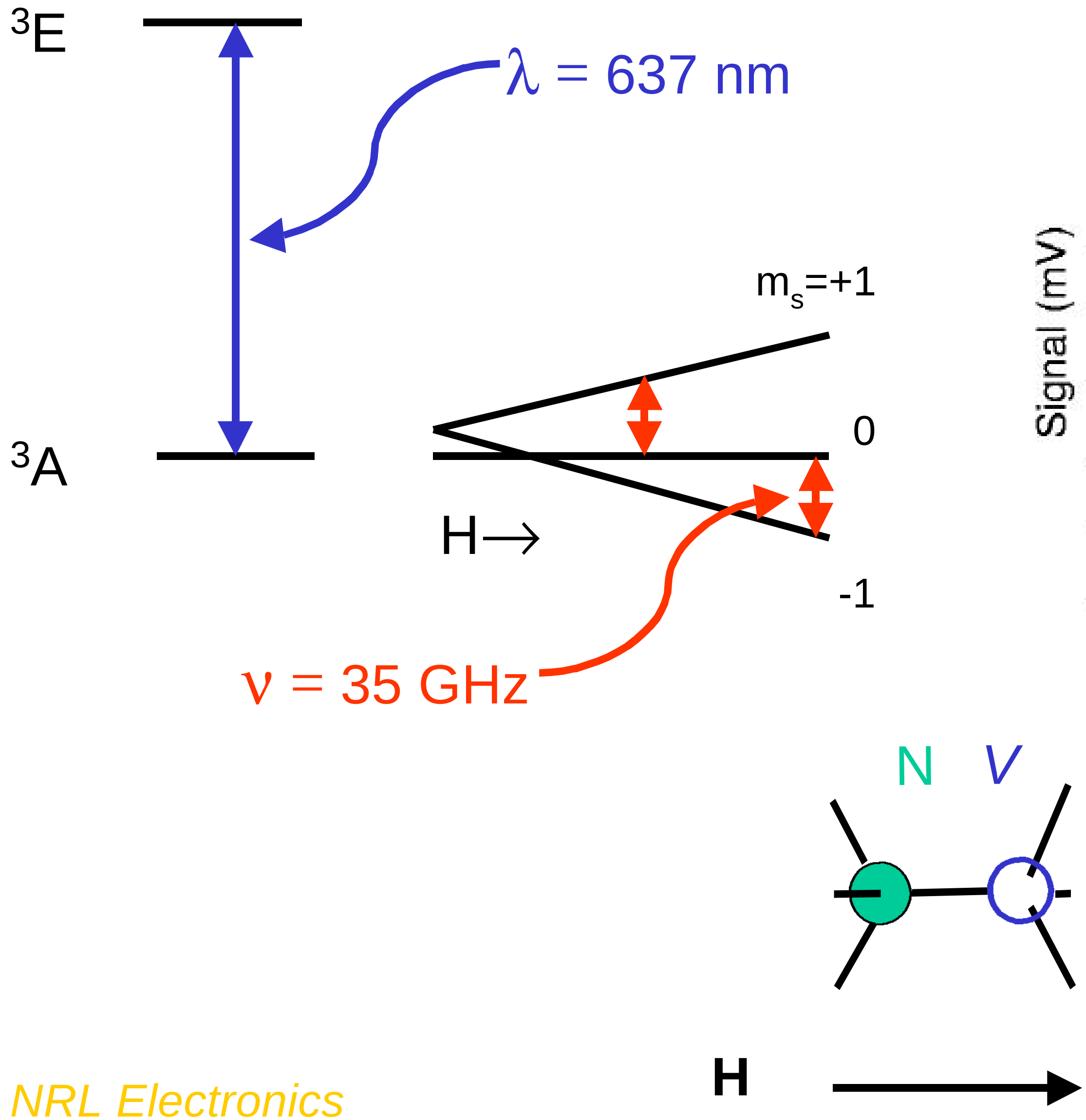


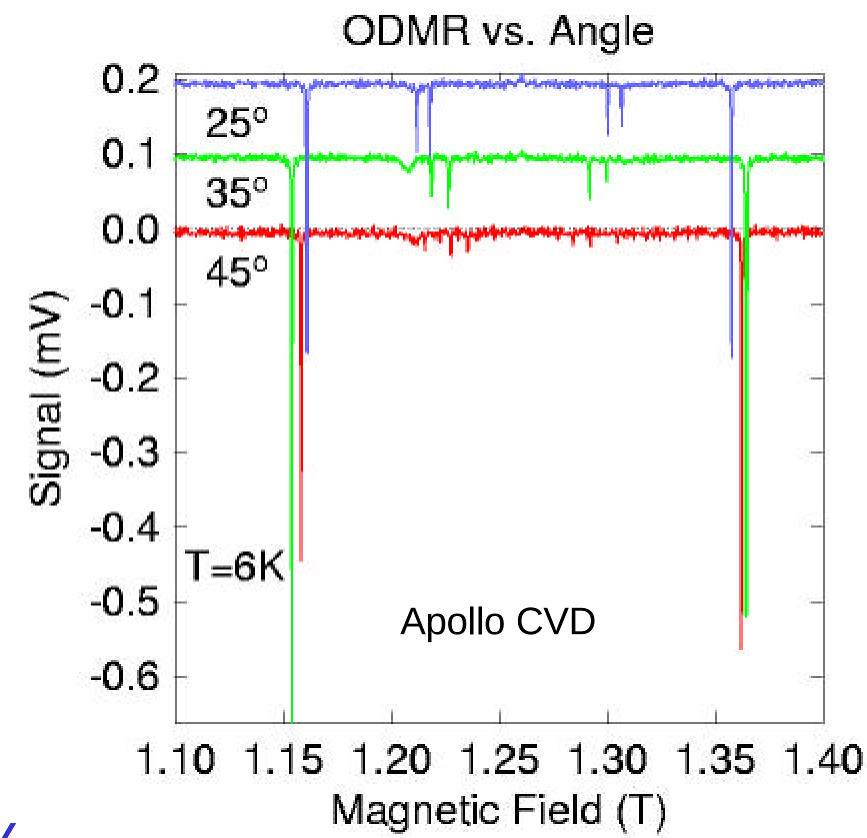




- Optical Properties
  - Large absorption cross section
  - Short excited state lifetime
  - High quantum efficiency
  - Emission depends on spin state



# The NV Center Qubit--Electronic Spin States
## Optically Detected Magnetic Resonance

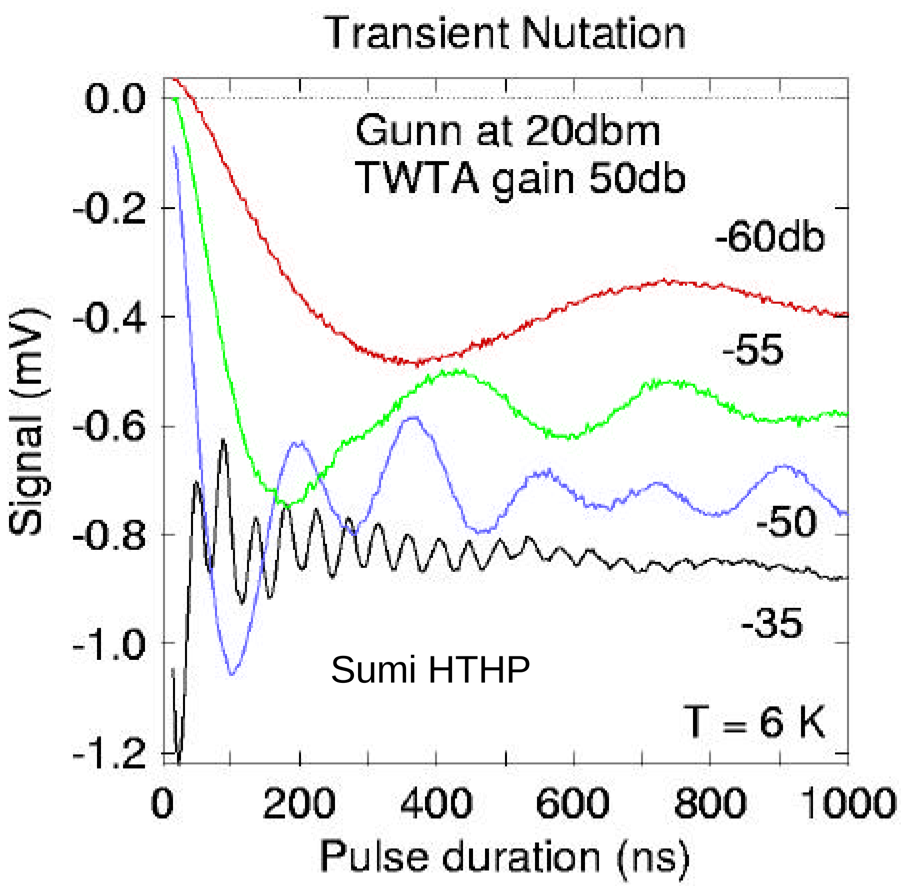


# Update

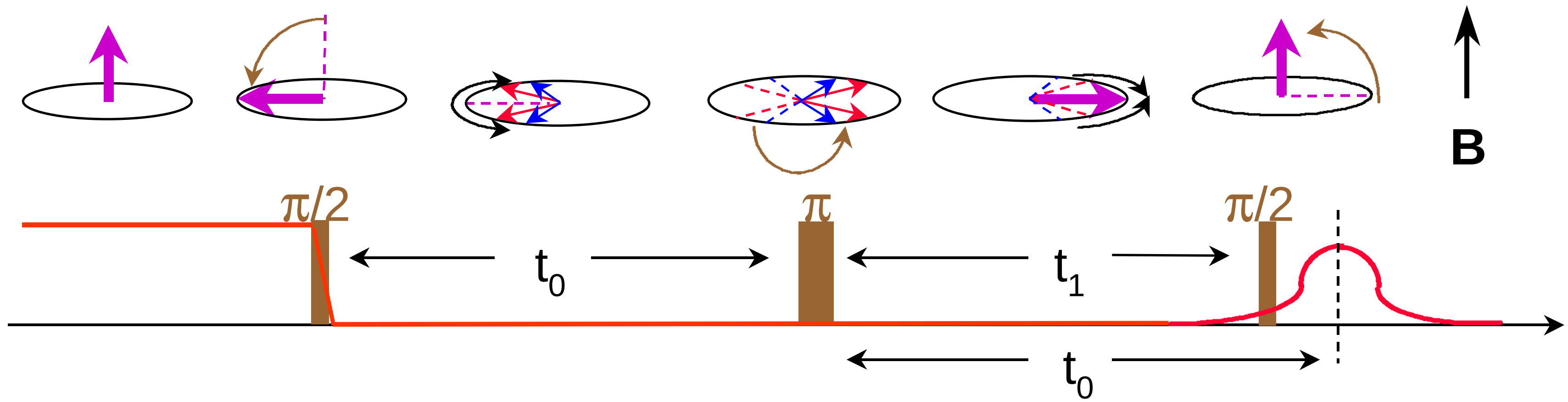
- Electron spin states √
- Polarize optically √
- Operate with microwave pulses
- Detect the result optically √

# Microwave pulse operators

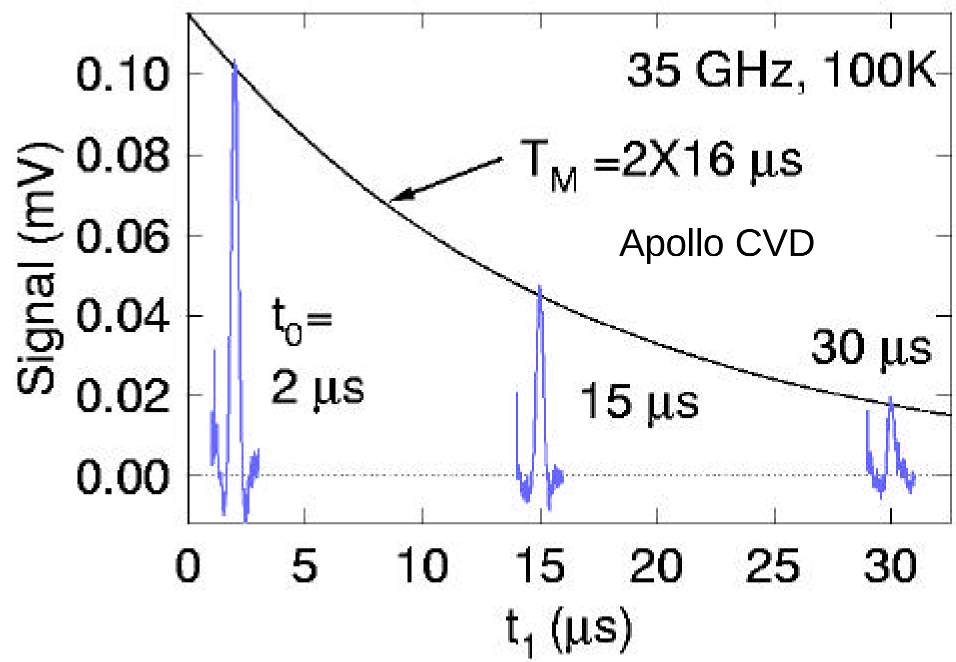



- Transient Nutation/Rabi flopping quantifies the operators
  - 110 mW Gunn Osc.
  - 10 W or 40 W TWTA
  - Microwave cavity with optical access
- 20 ns to 400 ns $\pi$-pulses

# Microwave-Pulse Operation
# Optically Detected Electron Spin Echo




- Hahn echo with π/2 probe pulse for optical detection
- 32 μs phase-memory time
- Spin echo (Refocusing) is the basic quantum operation with EM-pulses*



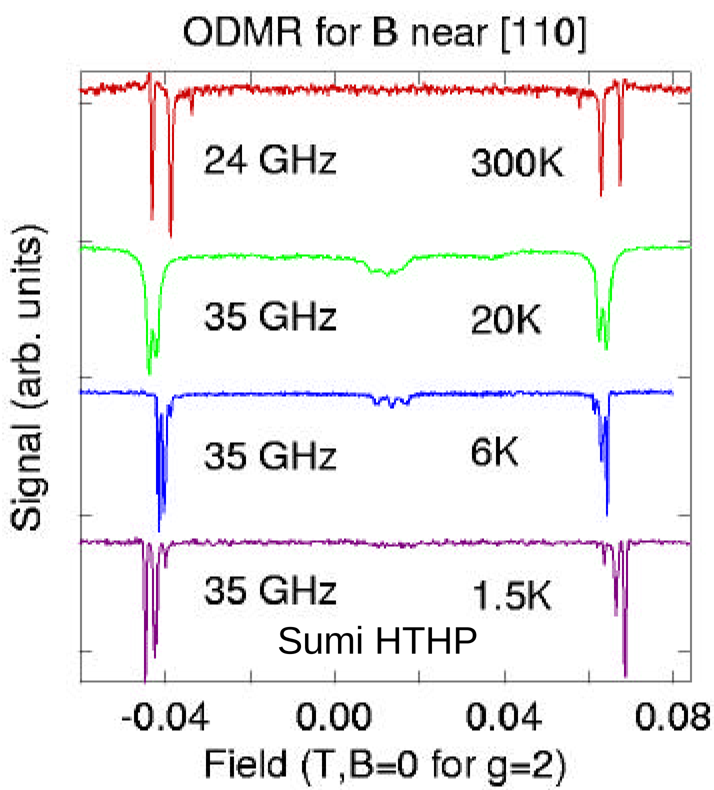

*Gershenfeld and Chuang, Science 98

# Long Lifetimes

| Sample | Low-T $T_M$ | [N-V] | [N] |
|---|---|---|---|
| Irradiated Sumitomo HTHP | 3.6 μs | 20 ppm ($7E17 cm^{-3}$) | 200 ppm |
| Apollo CVD | $\geq$32 μs | $\leq$5 ppm | $\leq$2 ppm |

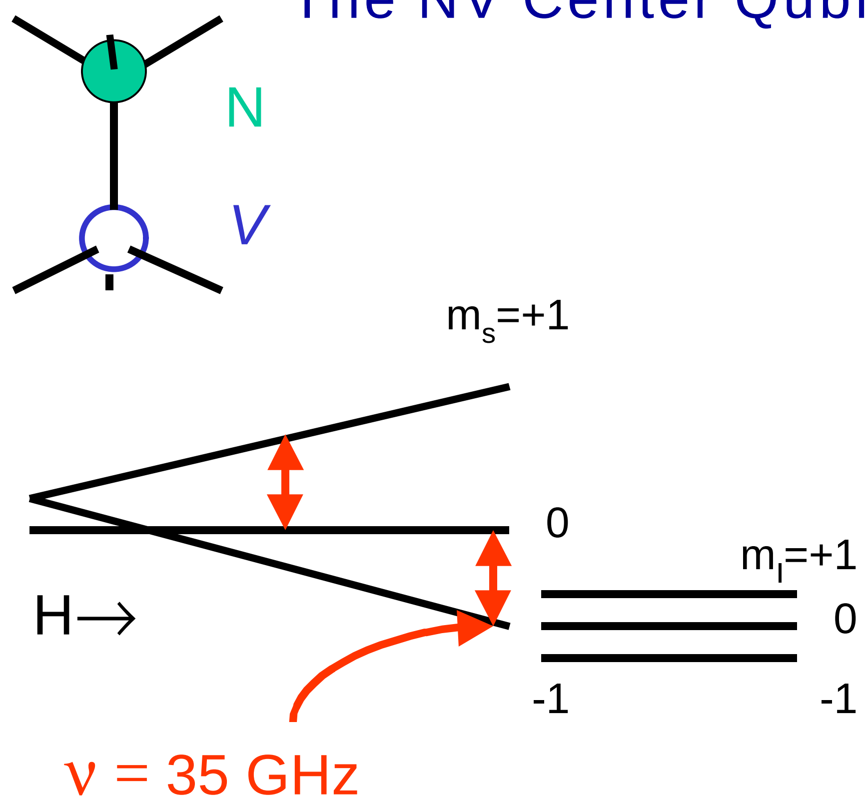
- For T$\leq$ 100 K, lifetime is limited by spin-spin interactions
- Best reported time is 41μs at 1.3 K (Van Oort et al., 1988)
- Much longer lifetimes (1 ms to 1 s) are expected for very dilute concentrations

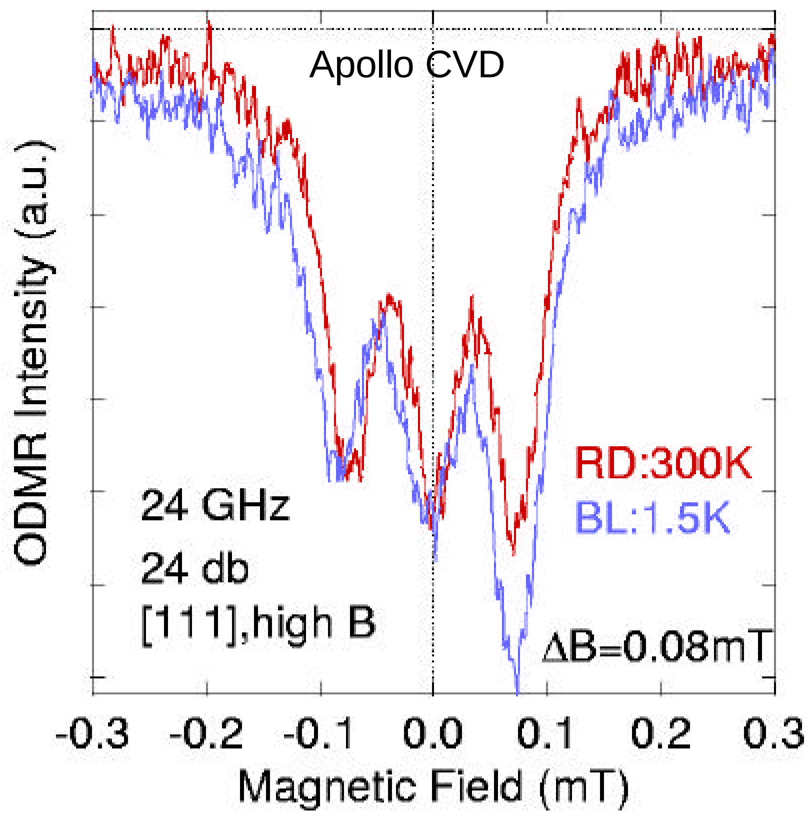
# Room Temperature




- Good optical and spin properties persist to room temperature
- $T_M \geq 9\ \mu s$
- High-temperature lifetime may be limited by phonon-modulation of the crystal field

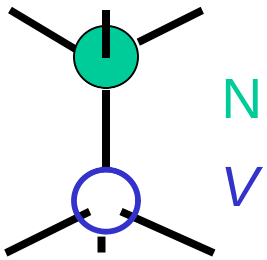
# The NV Center Qubit--Nuclear Spin States

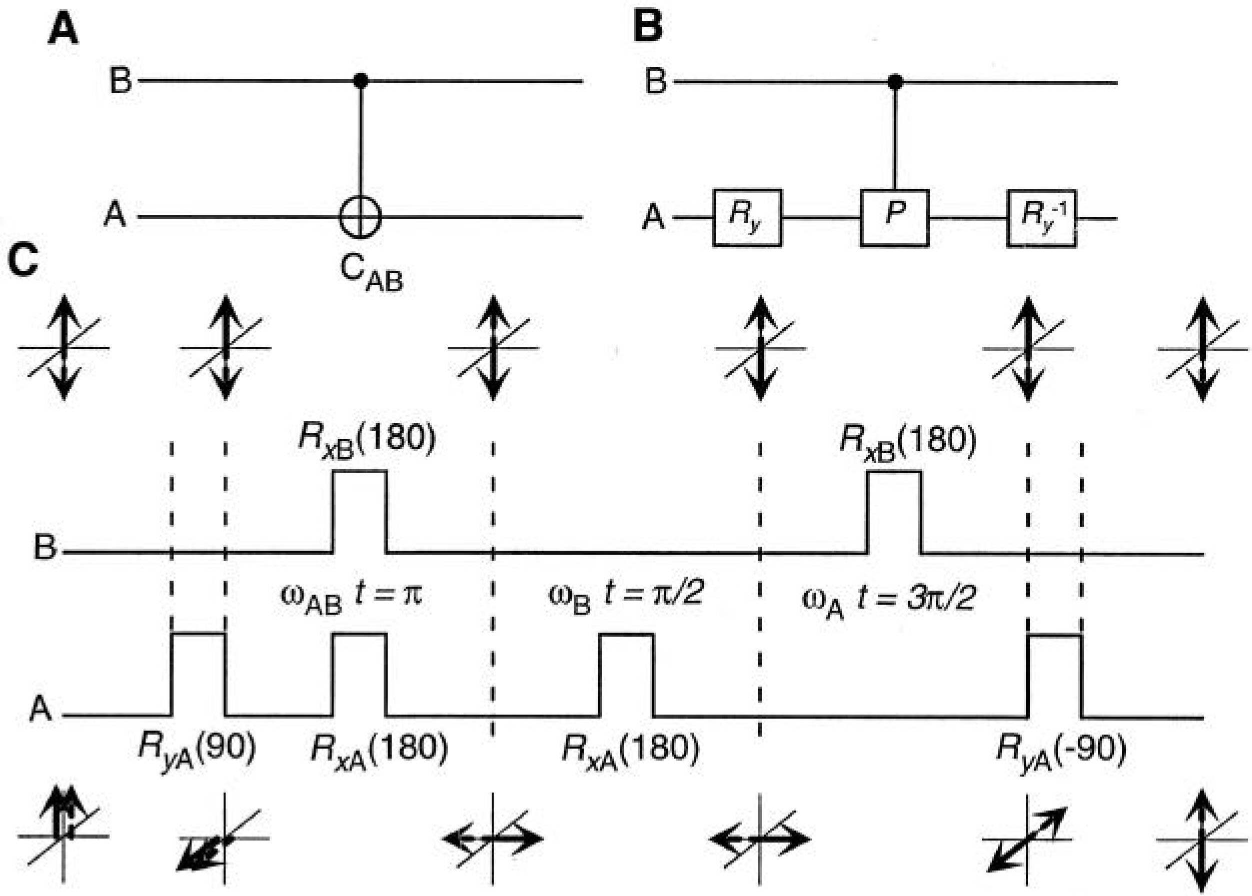



- $^{14}N$ is 99.6% I = 1
- ODMR component linewidth is about 0.08 mT (2.2 MHz)
- Partial nuclear polarization occurs at low temperatures

# Entanglement and the CNOT gate

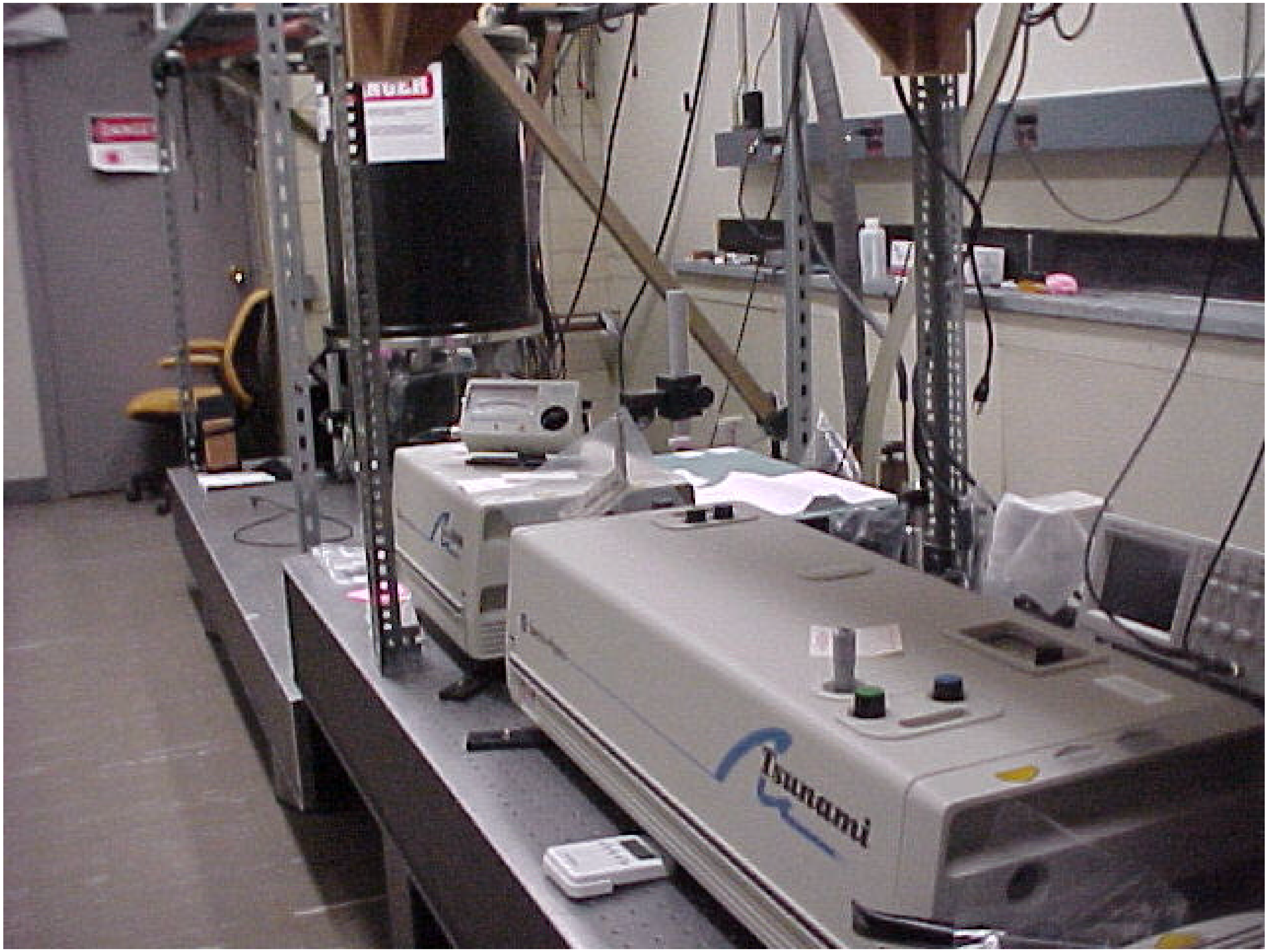



- Electronic spin and $^{14}$N nuclear spin as the A and B bits
- Microwave and radio-frequency pulse operators
- Gershenfeld and Chuang prototype for the CNOT gate

# *Summary*

- **Demonstration**
  - Spin of the NV-center as qubit
  - Optical polarization and detection
  - Microwave pulse operators
- **Long phase-memory times**
  - $\geq$ 32 μs for T $\leq$ 100 K
  - $\geq$ 9 μs for room temperature
  - Not optimized--longer times expected
- **Next step: CNOT gate**


Tsunami